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INVESTIGATION TOWARD OBTAINING SIGNIFICANTLY HIGHER MECHANICAL PROPERTIES OF AS-WELDED JOINTS IN HIGH-STRENGTH, HEAT TREATABLE ALUMINUM ALLOYS

By

F. R. Collins

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ABSTRACT

This report describes welding techniques, filler metal-parent metal selection and moderate temperature post-weld thermal treatments to achieve tensile strengths up to 72,000 pounds per square inch (psi) in welded heat treatable aluminum alloy sheet.

The aluminum-zinc-magnesium-copper (Al-Zn-Mg-Cu) alloys 7075 and 7178 welded with Al-Mg or Al-Mg-Zn filler metals gave higher as-welded strengths than the Al-Cu alloys 2219 and 2014. Although more susceptible to weld cracking than the Al-Cu alloys, 7075 and 7178 showed excellent response to post-weld aging when welded in either -W or -T6 tempers. A filler metal Al-4 Mg-2 Zn, gave welds almost as strong as parent filler metal with less cracking.

Tensile strengths of 70-72,000 psi were achieved in 1/8-in. 7178-T6 sheet welded with Al-Mg-Zn filler metal and post weld aged eight hours at 212°F plus three hours at 325°F. Strength in the bulge test was about 60,000 psi. Welds in 7075-T6 attained about 68,000 psi tensile strength

when post-weld aged 168 hrs at 212°F. Both tensile and bulge strengths were about 15,000 psi higher for post-weld aged than for as-welded joints.

Direct current, straight polarity tungsten inert gas welding with helium gave the most consistently high strengths. Consumable electrode, spray transfer welding was next best. Short-arc consumable electrode welding gave highest individual weld strengths, but consistency was poor.

INTRODUCTION

The high-strength, heat treated aluminum alloys such as 2014, 2024, 7075, and 7178 have strengths between 70,000 and 90,000 psi and are attractive materials for rocket cases and similar structures. On the basis of strength per unit weight, these aluminum alloys are equivalent to ferrous alloys of up to 300,000 psi tensile strength. Aluminum structures are more rigid because metal thickness is greater than equal strength and weight steel assemblies.

Fusion welding is the preferred method for fabricating light-weight structures because it gives leak-tight, smooth butt joints.

Inert gas shielded arc welds have been made in high-strength, heat treatable aluminum alloys, but strengths were usually less than half that of the base metal unless the welds were solution heat treated and aged. Even when welded assemblies were small enough to permit complete post-weld heat treatment, structural performance often was unsatisfactory, and performance could not always be predicted by tensile tests.

This investigation was initiated to develop arc welding procedures and select filler metal base metal combinations to achieve significantly improved weld strengths in high-strength, heat treatable alloys without post-weld solution heat treatment. A further object was to evaluate test methods to predict structural performance of welds in these alloys.

MATERIALS AND EQUIPMENT

The aluminum alloys investigated were 2219, 2014, 7075, and 7178 in sheets 0.064, 0.090, and 0.125 in. thick. Filler metals included 2319, 2014, 5556, 5052, 5154, 5554, 5652 M576, M577, M594, M595, and 7277. Nominal compositions of these alloys are shown in Table I.

Equipment for gas tungsten-arc welding consisted of:

1. Airco Model 3ADB 245CHABP 300 amp AC-DC Heliwelder
2. Airco Model HMH-E Heliweld automatic head
3. Oxweld type CM-37 machine carriage
4. 36-in. welding table with grooved copper backup

Gas metal-arc equipment used:

1. Miller Model CP 3VS variable slope DC welder
2. Aircomatic filler wire feeder, Model AHF-C, and Model AHF-B control
3. Aircomatic pull gun Model AH-35A
4. Airco No. 20 Radiagraph
5. 36-in. welding table with grooved copper backup

Esterline Angus Model AW recording voltmeter and ammeter were used for each weld.

Shielding gases were Linde high purity dry (99.995%) argon and Airco Grade A helium.

TEST METHODS

Inspection

All welds were inspected visually by the operator for smooth flow and complete penetration. Each weld was radiographed using a suitable penetrameter and the films compared with known standards. No welds were further tested that did not exhibit a degree of soundness as least as good as required for Class 2 welds under Army Ballistic Missile Agency purchase description ABMA-PD-R-27.

Tensile Tests

Standard sheet-type tensile specimens shown in Figure 1 were used for all gages of welded sheet for both the full-section and flush-bead samples. Special tensile specimens shown in Figure 2 were used in the portion of this investigation concerned with the development of test methods. Type HE-121-R2B Tatnall Metalfilm strain gages and appropriate instrumentation were used to measure local strain.

Bulge Tests

The 8-in. nominal diameter hydrostatic bulge tester shown in Figures 3 and 4 was used to perform all the bulge tests shown in this report. As shown in Figure 5, bulge height determines radius of curvature and stress is calculated according to the formula.

$$\text{Stress} = \frac{PR}{2t_o}$$

Where: P = Pressure psi R = Radius t_o = Sheet thickness

Corrosion Resistance

The specimens shown in Figure 6 were used to determine susceptibility to stress corrosion cracking. In this design pairs of specimens are stressed to 75 per cent of the yield strength of the joint and exposed to alternate immersion (10 min in, 50 min out) in 3-1/2 per cent sodium chloride solution. General corrosion attack was evaluated by exposing unstressed specimens to the same environment. Solution potential surveys were conducted in a solution of 53 gm NaCl, 3 gm H_2O_2 per liter of distilled water. Potentials of the selected areas were determined by masking the remainder of the specimen with wax before immersion. The reference electrode was 0.10 normal calomel.

WELDING PROCEDURE

General

A standard weld specimen consisting of two pieces of aluminum sheet 7 x 16 in. groove welded along the 16 in. dimension was used throughout the investigation except for the cylindrical pressure vessels. The sheets were prepared by sawing or shearing to size degreasing with a suitable solvent, etching in caustic and nitric solutions, and hand filing the abutting edges clean and square. The pieces were assembled in the welding hold-down table with run-in and run-off tabs at the ends. All welds were made in the flat position by completely automatic procedures. Amperes and volts were recorded automatically. The operator noted and recorded process variables such as travel speed, wire feed speed, gas composition, and flow rate.

After welding, 14-in. square panels were provided for bulge testing and the remainder of the 16-in. specimens (at the finish end of the weld) was used for tensile specimens. Each panel thus provided one bulge and two tensile specimens.

Gas Metal Arc Welding (MIG and MIG Short-Arc)

The Airco pull gun was adapted for completely automatic welding by attaching it to an adjustable arm on the travel carriage. Mechanisms were provided for vertical and horizontal movement as well as adjustment for fore-hand or back-hand angle. The welding power supply and wire drive unit were adjustable to provide either conventional spray-type or short-arc droplet-type metal transfer. Typical welding parameters are listed in Table II

Gas Tungsten-Arc Welding (DCSP-TIG)

This process employed the automatic voltage control tungsten-arc head, helium gas, and direct current, straight polarity. The automatic wire feeder was adjustable so that 3/64, 1/16, or 3/32-in. diameter filler wire could be used. In all cases the welding torch was mounted exactly perpendicular to the sheet. Electrodes of 2 per cent thoriated tungsten were used exclusively. Typical welding parameters are shown in Table II.

RESULTS

Choice of Welding Method

Direct current, straight polarity gas tungsten-arc (DCSP-TIG) welding proved to be the most reliable method investigated. Sound welds were produced in all combinations of plate and filler metals examined, and weld strengths were consistent.

The gas metal-arc (MIG process) gave consistent results but strengths were always lower than for DCSP-TIG welds in similar alloys. MIG welds in 7075 and 7178 tended to have transverse root cracks when the lower magnesium content or zinc-containing filler metals were used, because penetration was shallower than for TIG welds, leaving unalloyed base metal at the root.

Consumable electrode (MIG) short-arc welding gave the highest as-welded properties and is the preferred method where no backup can be used, since uniform penetration beads were obtained with free drop-through. It was often difficult, however, to achieve just the right amount of penetration without undercutting. The MIG short-arc method was also critical with respect to the composition and melting characteristics of the filler metal. It was easy to obtain fully penetrated welds free of undercutting with 2319, 4043, 5154, and 5554 alloy electrodes. More difficulty was encountered with 5556 and 5356 alloy electrodes. Shielding gas of two parts helium, one part argon was preferred.

Little success was achieved in producing multipass MIG short-arc welds in 1/8-in. sheet with 0.030-in. diameter electrode because of poor interpass fusion. Thus, for the heavier sheet gages a single pass using 0.047-in. diameter electrode was highly preferred. In MIG short-arc welding the maximum travel speed was approximately 60 in. per min since beyond this speed the arc became unstable. Conventional spray-transfer arcs were found to be stable at travel speeds up to 300 in. per minute. Another difficulty experienced with MIG short-arc welds was the critical control of exact arc location, because of pitch and cast in the spooled electrode. A longer-than-standard contact tube for the welding head proved beneficial. MIG short-arc welds were somewhat hard to start and it proved best to use a contact tube to work distance of 1 to 1-1/2 in. until the arc was firmly established on a run-in tab, then reduce it to the 1/4 to 3/8-in. required for accurate control of arc location during welding. Welds were best when the torch was mounted to have a forehand angle of about 15 degrees.

Typical bead contours produced in 1/8-in. thick aluminum sheet by DCSP-TIG and MIG short-arc processes, respectively, are shown in Figures 7 and 8.

Aluminum-Copper Alloys, 2219 and 2014

The Al-Cu alloy 2219 was shown previously to be the most weldable of the commercial high-strength, heat treatable aluminum alloys, being clearly superior to other alloys of this group with respect to freedom from cracking, smooth flow, and reproducibility of weld strengths.

The highest as-welded strength in 2219 alloy was achieved in the -T87 temper where both tensile and bulge tests showed an average strength of 45-50 KSI. Yield strength was improved about 10 KSI by welding 2219 in the -T37 temper and post-weld aging to the -T87 temper. Since previous work with the Al-Cu alloys showed little promise for substantially improved weld strength without post-weld solution heat treatment, it was decided to shift the investigation to the stronger Al-Zn-Mg-Cu alloys. Comparative strengths of welded 2219 and 2014 alloys are shown in Table III.

Aluminum-Zinc-Magnesium-Copper Alloys, 7075 and 7178

General Considerations -- Alloys of this group have the highest strength of any of the commercial aluminum alloys but are the most difficult to weld. Strengths of these alloys are usually less sensitive to the rate of quench from solution heat treating temperature than the Al-Cu alloys. Under proper conditions, welds in the Al-Zn-Mg-Cu alloys gain a large measure of strength from the quench achieved in the welding jig. Thus, despite the relatively poor flow and higher susceptibility to weld cracking, it is possible under carefully controlled conditions to achieve higher weld strength in these alloys than in the Al-Cu types.

Previous experience showed that the Al-Mg filler metals were the best choice for strength, reasonable freedom from cracking, and ductility. It was also known that the strength of such welds was controlled primarily by: (1) dilution of the filler metal by melted base metal, (2) quench rate, (3) natural or artificial aging, and (4) amount of weld bead reinforcement.

When diluted during welding by base metals 7075 or 7178, the weld bead is an alloy responsive to heat treatment. A reasonably rapid quench, such as that achieved by automatic welding in heat-absorbing fixtures, produces a solution heat treated weld area that age hardens at room or elevated temperature. Assuming aging of welds proceeds in the same general manner as solution heat treated base metal, welds in 7075 or 7178 should naturally age in one month to about 75-80 per cent of the strength achieved after one year, when hardening is substantially complete.

As-Welded Properties

Table IV shows the mechanical properties of MIG short-arc and DCSP-TIG welds in 7178 and 7075 alloys with no subsequent heat treatment. Highest strengths were obtained in 0.064-in. sheet welded using 7075 or 7277 filler metal. Tensile and bulge strengths of up to 65 KSI were obtained. Welds were extremely difficult to produce using these filler metals because of excessive hot-short weld cracking. These filler metals are not considered commercially usable on 7075 and 7178 base metals, and 5556 is generally recommended.

In 0.090-in. and 1/8 in. thick sheet, highest as-welded properties were obtained using MIG short-arc with 5556 filler metal. Tensile strengths of 55 to 60 KSI were attained with the corresponding bulge strengths of 40 to 53 KSI. Similar DCSP-TIG welds made with 5556 filler metal showed 50 to 55 KSI tensile strength and 50 KSI bulge strength. Although the highest values were lower than the highest attained by the MIG short-arc method, DCSP-TIG welds were more reproducible. MIG welds made using standard spray-transfer welding conditions were neither as strong as the MIG short-arc welds nor reliable as the DCSP-TIG welds.

Post-Weld Aging

Many aluminum alloys can be welded in the solution heat-treated temper (-W) and post-weld aged to produce higher mechanical properties than can be attained in the as-welded condition (Ref. 1). Alloys 7075 and 7178 proved responsive to this treatment. Post-weld aged MIG short-arc welds in 7178 and 7075-W alloys made with 5556 electrode showed improved properties over as-welded joints. Tensile and bulge strengths were 58 to 60 KSI with reasonable correlation between bulge and tensile tests.

7075 and 7178 alloys are easy to form in the -W (as-quenched) condition. Unfortunately, these alloys age rapidly at room temperature and must, therefore, be formed and welded within a few hours after quenching to avoid substantial age hardening. It is possible, of course, to store flat sheet in refrigerated containers to prevent natural aging, but this is not usually a commercially economical or feasible procedure for formed structures that are to be welded.

In welds produced under rapid chill conditions, only a small portion of the total structure contains partially melted, solution heat treated, annealed and over-aged zones. It was thought it might be feasible to weld fully aged (-T6) sheet, then age the welded assembly at a temperature that would cause precipitation hardening in the heat-affected zones, yet allow the unaffected parent metal to remain substantially unchanged. Reheating data for 7075 and 7178 alloys showed that temperatures of 200 to 325°F had little, if any effect on the mechanical properties of -T6 temper sheet (Ref. 2).

Welds in 7178 and 7075-T6 sheet were aged one week at 212°F in the first tests of this procedure. This rather low temperature was chosen to be sure of not affecting the base metal and to achieve the desirable fine precipitate in the weld area.

Tensile strengths up to 75 KSI were attained in 0.090-in. 7178-T6 base metal welded with M576 (4 Mg-2Zn) filler metal and aged one week at 212°F. Strengths of 65 to 68 KSI were obtained in 1/8-in. 7178 and 7075 sheet, reflecting the slower quench achieved in the thicker sheet. Welds made with the zinc-containing filler metals M576, M577, M594, and M595 were slightly stronger than those made with the Al-Mg filler wires such as 5556 and 5154. The lower Mg content filler metals, 5554 and 5052, produced tensile strengths almost as high as the high Mg and Al-Mg-Zn filler metals but bulge strength was severely reduced, and hot-short cracking was more prevalent. This indicates that approximately 3-4 per cent Mg is needed in the filler metal under the conditions of dilution achieved in these tests. This was especially noticeable in the bulge tests where failures of welds made with low Mg filler metals usually occurred as transverse cracks through the weld bead, indicating low ductility.

It was recognized that the aging treatment of one week at 212°F was not a commercially feasible procedure; therefore, shorter treatments, 24 hrs at 212°F and step aging 4 hrs at 212°F + 8 hrs at 315°F and 8 hrs at 212°F + 3 hrs at 325°F were tried. All treatments gave substantial improvement over as-welded strengths. The step aging treatments appeared to reduce ductility slightly and increased notch sensitivity, as evidenced by the greater spread between the bead-on and the bead-off bulge test specimens. For these treatments the bulge strength was almost invariably higher for specimens from which the weld bead had been machined flush prior to testing.

As for the as-welded specimens, MIG short-arc welds that were post-weld aged had average strengths slightly lower than those achieved by DCSP-TIG and were less consistent among samples given the same treatment.

The response of various parent-metal filler-metal combinations to post-weld aging treatments is shown in Table IV. Here the effect of aging treatment and filler metal on the strength of welds in both bulge and tensile tests is apparent. Two trends are particularly noteworthy. First, under the conditions of dilution achieved by the welding methods in this test there appears to be little, if any, advantage of using filler metal stronger than M576 (4 Mg-2 Zn). Alloys of higher Zn and/or Mg content did not increase weld strength. All full-section and most reduced-section samples failed outside the bead. In addition, filler metals containing either higher Zn or less Mg than M576 had increased sensitivity to hot-short weld cracking, making them more difficult to use in production conditions. The low ratio of bulge strength to tensile strength was quite apparent for those combinations of filler metal and aging treatment that produced less ductile welds. Figure 9 shows the effect of aging treatment on the tensile and bulge strengths of welds in 1/8-in. 7178-T6 with M576 filler.

Special Tensile Tests

The bulge test imposes equal biaxial stresses on test specimens, and the usual tensile test involves primarily uniaxial stress. Most rocket cases and other pressure vessels are cylindrical, and with internal pressure develop hoop stress about twice the longitudinal stress. Fabricating and testing cylindrical pressure vessels is costly, and it is difficult to produce welds as good as those in flat sheet without using costly fixtures. Previous experience showed that bulge tests were better than tensile tests to predict performance of cylindrical vessels, but correlation was not as good as desired.

The special tensile-type specimens shown in Figure 2 were devised in an attempt to provide a simple test that would predict performance under unequal biaxial stress. The short, wide type A specimen was designed to develop biaxial stress under uniaxial load. Biaxial strains, measured at the center, showed the longitudinal stress was about 2-1/2 times the transverse stress. Because of stress concentration, however, longitudinal stresses at the edges of the specimen were about twice that at the center. These specimens failed at low nominal stress when the longitudinal edge stress reached the tensile strength typical for standard tensile specimens. Type A specimen was abandoned as unsuitable, since it did not produce the desired stress pattern.

Occasionally it has been proposed that welded high-strength alloy structures often fail at lower nominal stress than tensile specimens because a long length of weld, more likely to contain defects, is tested. Specimen type C, Figure 2, was used to test a 15-in. weld under uniaxial tension, and strengths were compared with those of type B specimens that were 1-1/2 in. wide. For as-welded 1/8-in. 7178-T6 with 5556 filler, the wide and narrow specimens gave nearly identical strengths. MIG welds averaged 47.5 KSI TS for the narrow specimens, 48.8 KSI TS for the wide. TIG welds averaged 51.1 KSI TS and 54.7 KSI TS, respectively, for the narrow and wide specimens. Ten-inch elongation was about 0.1-0.2 per cent, just equal to or less than the permanent offset used to determine yield strength. Base metal properties were 88.1 KSI TS, 9.9 per cent 10-in. elongation.

None of these specimens was more suitable to predict structural performance than the standard tensile and bulge tests. Emphasis in this portion of the investigation has been shifted to a comparison among standard tensile, bulge, and cylindrical pressure vessel tests. Strain gages are being used to determine if stress distribution in structures having welds of relatively low ductility is markedly different from unwelded or ductile welded structures.

Microstructures

Figure 10 shows, at low magnification, a typical weld in 7178-T6 and the specific areas selected for examination at higher magnification.

The weld beads (Area A) in both as-welded (Figure 11) and post-weld aged (Figure 12) 7178 alloy had small dendritic structures that were typical of fast-chilled welds. No changes identifiable under the light microscope occurred during post-weld aging The heterogeneous structure shows a considerable amount of Zn-Mg-Cu rich material out of solid solution. A small amount probably was taken into solution during the short interval the weld was in the heat treating temperature range during cooling. An extremely small interdendritic spacing, however, would be required to achieve homogeneity, since the weld cools through the solution heat treating temperature range in a few seconds (Ref 3).

The transition zone between cast and wrought metal (Area B) is shown in Figure 13. Some isolated pockets of high Zn-Mg-Cu constituent in the predominantly wrought structure at the left show that this region reached a temperature higher than the solidus of the parent metal, causing partial melting. Although this temperature was high enough, under equilibrium conditions, to redissolve the fine precipitate found in -T6 temper parent metal, much of it remained. Upon aging, visible precipitate increased only in the wrought metal.

Area C, which showed little if any partial melting, attained a temperature high enough to redissolve some precipitate (Figure 14)*. The amount of precipitate increased noticeably on post-weld aging (Figure 15)*. This is the area in which failure normally occurred in both as-welded and post-weld aged joints. The increased precipitation hardening on aging appears to account for the higher strength achieved by aged welds.

* Fine precipitation not clear in reproduction of figures.

The over-aged zone, area D, was heated during welding to a moderate temperature, which caused precipitation of more of the alloying constituents (Figure 16) than in the -T6 temper base metal. Figure 17 shows that this over-aged zone was not visibly affected by post-weld aging at 212°F. Although some loss of strength must have occurred, this area remained stronger than area C.

The unaffected base metal further from the weld than area D was not examined since no significant change in structure or properties was expected.

Welds in 7075-T6 were similar in appearance to those in 7178-T6, but some important differences were noted. In area C (Figures 18 and 19), 7075 showed less precipitate than 7178, both before and after aging, and on aging had a smaller increase in precipitation. Area D behaved similarly (Figures 20 and 21). In both areas, grain boundaries were more heavily outlined for 7075 than 7178. This condition seems to correlate with the generally lower ductility and bulge height of welded 7075.

Resistance to Corrosion

The solution potential survey provides a rapid method to predict corrosion behavior of welds. Areas of highest negative potential (anodes) corrode preferentially to protect those of lower potential (cathodes).

In a weld, the optimum condition is to have the weld bead, heat affected zones, and base metal all of the same potential to avoid selective attack. Next best is to have the weld area cathodic to the base metal so that the small weld area is protected by the relatively large area of anodic base metal. An anodic weld area is least desirable, since this small area will corrode rapidly, attempting to protect the large area of cathodic base metal. The depth of selective attack tends to increase with: (1) difference in potential, and (2) reduction in anode area.

Solution potentials were measured at the center of the weld, 1/8-in. from the edge of the weld and 4-in. from the weld in unaffected base metal. The unmasked areas in contact with the $NaCl-H_2O_2$ solution were strips about 1/8 in. wide, parallel to the weld. All readings were stable within two hours after immersion.

As shown in Figures 22 and 23, the heat affected zones of as-welded 7075-T6 and 7178-T6 were strongly anodic. In corrosive environments, welds in 7075 would probably show preferential attack in the heat-affected zone. Welds in 7178 should experience severe local attack since the heat-affected zone was quite anodic to both weld bead and base metal. Aging 24 hours at 212°F reduced the spread in potentials slightly, but selective corrosion in the weld area still would be expected. In both the as-welded and aged 24 hrs at 212°F conditions, the potentials observed in the weld and heat-affected zones correlated well with the established typical potentials for solution heat treated, unaged base metal (7075-W — -870 m.v.). Potentials of the base metal were not significantly affected by post weld aging. The longer time or step aging treatments gave much more uniform solution potentials among the several areas. All should eliminate or greatly reduce selective attack, since the weld areas either had the same potential as or were slightly cathodic to the base metal.

To achieve the optimum combination of predicted corrosion resistance and strength, it presently appears that welded 7075-T6 should be aged 168 hrs at 212°F and welded 7178-T6 aged 8 hrs at 212°F plus 3 hrs at 325°F. This is a tentative recommendation, since actual corrosion tests and stress corrosion tests are still in progress.

CONCLUSIONS

1. Tensile strengths of 72,000 psi can be achieved in welded 7178-T6 aluminum sheet by DCSP-TIG welding with Al-4-Mg-2 Zn filler metal and post-weld aging.

2. Al-Zn-Mg-Cu alloys 7178 and 7075 are more difficult to weld than most Al-Cu alloys, but sound, crack-free welds are stronger in both as-welded and post-weld aged conditions.

3. Direct current straight polarity tungsten arc welding with helium shielding is preferred to spray transfer or short-arc consumable electrode welding for consistently high strength welds.

4. Anticipated resistance to corrosion of welded 7075 and 7178 alloy sheet is improved by post weld aging.

5. The hydraulic bulge test is presently the most satisfactory simple test to biaxially stress welds in high strength, heat treatable aluminum alloys.

6. Improved base metals and filler metals are required to reduce cracking and increase strength and ductility of welds in Al-Zn-Mg-Cu type alloys.

RECOMMENDATIONS FOR FUTURE WORK

It is recommended that future attention be directed toward the following specific programs:

1. Evaluate effect of base metal grain size, cell size, and grain orientation on weld strength and ductility.
2. Develop improved Al-Zn-Mg-Cu type base metals and filler metals to reduce weld cracking and increase weld strength and ductility.
3. Survey test methods to improve accuracy of predicting full-scale structural performance of welds in high-strength, heat treatable aluminum alloys.
4. Improve welding methods to achieve highest strength, reliable welds.

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2. Nock, J. A. Jr., "75S - Alcoa's New High Strength Aluminum Alloy," Metals and Alloys, Oct. 1944.
3. Brown, Paul E. and Adams, C. M. Jr., "Fusion Zone Structures and Properties in Aluminum Alloys," Welding Journal, Research Supplement 39, No. 12, 520-s to 524-s, December 1960.
4. Collins, F. R., Nelson, F. G., and Robinson, L B., "A High Strength Weldable Aluminum Alloy," Metal Progress, November 1961.
5. Robinson, L B., Collins, F. R., and Dowd, J. D., "The Hydraulic Bulge Test for Welded Aluminum Sheet," The Welding Journal, December, 1961.

TABLE I

NOMINAL COMPOSITIONS - BASE AND FILLER METALS

BASE METALS

Alloy	Cu	Si	Mn	Mg	Zn	Cr	Ti	V	Zr	
2219	6.3	--	0.3	--	--	--	--	0.10	0.15	
2014	4.4	0.8	0.8	0.4	--	--	--	--	--	
7075	1.6	--	--	2.5	5.6	0.3	--	--	--	
7178	2.0	--	--	2.7	6.8	0.3	--	--	--	

FILLER METALS

Alloy	Cu	Si	Mn	Mg	Zn	Cr	Ti	V	Zr	
2319	6.3	--	0.3	--	--	--	0.15	0.10	0.15	
5556	--	--	0.8	5.25	--	0.10	0.10	--	--	
5554	--	--	0.8	2.75	--	0.10	0.10	--	--	
5154	--	--	--	3.5	--	0.25	--	--	--	
5052	--	--	--	2.5	--	0.25	--	--	--	
5652	--	--	--	3.5	--	0.25	--	--	--	Low Fe and Si
7277	1.25	--	--	3.0	4.0	0.25	--	--	--	
M576	--	--	0.50	4.0	2.0	0.10	0.10	--	--	
M577	--	--	0.10	4.0	4.0	0.10	0.12	--	--	
M594	--	--	0.10	2.0	4.0	0.10	0.12	--	--	
M595	--	--	0.10	3.0	3.0	0.10	0.12	--	--	
4043	--	5.0	--	--	--	--	--	--	--	

TABLE II

TYPICAL WELDING CONDITIONS FOR 0.064, 0.090, AND 0.125" HIGH STRENGTH ALUMINUM ALLOY SHEET, SQUARE GROOVE WELDS

Gas Metal Arc Welds (Short Arc)

Sheet Thickness Inches	Electrode Dia.	Electrode Feed in/min	Travel Speed in/min	Backup(1) Groove	Root(2) Opening Start-End	Amperes	Arc Volts	Open Circuit Volts	Slope, Volts/100 amps	Gas: Helium CFH	Gas: Argon CFH
0.064	0.030	340	40	11/32x1/4	0-1/16"	100-120	10-12	19	6	33	17
0.090	0.047	230	36	11/32x1/4	0-3/32"	110-120	13-14	25	6	33	17
0.125	0.047	265	30	11/32x1/4	0-1/8"	130-140	14-15	25	5	33	17

Gas Metal Arc Welds (Spray Transfer)

Sheet Thickness Inches	Electrode Dia.	Electrode Feed in/min	Travel Speed in/min	Backup(1) Groove	Root(2) Opening Start-End	Amperes	Arc Volts	Open Circuit Volts	Slope, Volts/100 amps	Gas: Helium CFH	Gas: Argon CFH
0.125	0.047	310	40	5/32x1/16	0-0	190	25	40	9	33	17

Gas Tungsten Arc Welds (D.C. Straight Polarity)

Sheet Thickness Inches	Electrode(3) Diameter	Cold(4) Wire Feed in/min	Travel Speed in/min	Backup(1) Groove	Root(2) Opening	Amperes	Arc Volts	Helium CFH
0.064	3/32"	40	20	5/32x1/16	0-0	100-120	12	30
0.090	3/32"	50	20	5/32x1/16	0-0	160-170	12	35
0.125	1/8"	60	20	5/32x1/16	0-0	200-210	12	40

1 Cylindrical Groove _" wide x _" deep
2 For 16" long welds, with available hold down pressure
3 2% Thoriated tungsten
4 Based on 1/16" dia wire - Equivalent amount of 3/64" or 3/32" dia can be used.

TABLE III

PROPERTIES OF WELDS IN 2219 AND 2014 ALLOYS

Sheet Temper	Sheet Gage	Weld ⌘ Method	Tensile Tests TS KSI	Tensile Tests YS KSI	Tensile Tests % El 2-in.	Tensile Tests S KSI	Bulge Tests TS KSI	Bulge Tests Height Inches	Bulge Tests S KSI
2219									
-T87	.064	SA	46	37	1.9	0.5	47	.37	2.1
-T37, aged to -T87	.064	SA	53	49	1.3	1.6	54	.47	1.8
-T31, aged to -T81	.064	SA	52	48	1.5	2.4	55	.54	1.4
-T87	.064	DCSP	47	34	1.5	1.2	50	.42	1.5
-T37, aged to -T67	.064	DCSP	53	47	1.6	1.4	44	.48	0.4
-T31, aged to -T81	.064	DCSP	53	45	1.2	0.4	42	.44	1.4
-T87	1/8	DCSP	45	29	2.2	1.0	48	.45	1.6
-T37, aged to -T87	1/8	DCSP	50	41	1.8	1.0	47	.43	1.1
2014									
-T6	.064	SA	50	47	1.0	2.9	47	.40	5.9
-T6	.064	DCSP	49	46	1.5	1.7	40	.35	2.9

⌘SA --- Gas Metal Arc, "Short-Arc" with .030" electrode, 1 He/1A gas mixture.

⌘DCSP- Gas tungsten arc, straight polarity, He gas, 1/16" cold wire feed.

Standard deviation (S) = $\sqrt{\frac{(x - \bar{x})^2}{n - 1}}$

TABLE IV

PROPERTIES OF WELDS IN 7075 AND 7178 ALLOY SHEET
(Weld Bead Intact)

AVERAGES, MINIMUM OF 3 BULGE TESTS, 3 TENSILE TESTS

Alloy and Temper	Thickness Inches	Weld Method	Filler Alloy	Post-Weld Treatment	Tensile Tests TS KSI	Tensile Tests YS KSI	Tensile Tests % El (2")	Bulge Tests TS KSI	Bulge Tests Height Inches	Bulge Tests S KSI
7075-T6	.064	SA	5556	None	56	55	0.7	42	.41	--
7075-T6	.064	DCSP	7075	None	63	55	1.7	55	.45	--
7075-T6	.064	DCSP	5154	None	52	49	1.7	47	.40	--
7075-T6	.064	DCSP	5052	None	51	47	1.5	45	.40	--
7075-W	.064	SA	5556	Age -T6	55	51	1.0	61	.37	--
7178-T6	.064	SA	5556	None	57	56	0.8	53	.42	--
7178-T6	.064	DCSP	7075	None	65	61	1.3	46	.40	--
7178-T6	.064	DCSP	7277	None	63	60	1.0	47	.40	--
7178-W	.064	SA	5556	Age -T6	58	51	0.9	60	.39	--
7178-T6	.090	DCSP	M576	None	54	50	0.8	--	--	--
7178-T6	.090	DCSP	M576	A	69	64	1.0	60	.45	1.4
7178-T6	.090	DCSP	M576	B	75	73	1.0	52	.40	--
7178-T6	.090	DCSP	M576	C	73	69	0.9	52	.45	--
7178-T6	.090	DCSP	M576	D	73	69	1.0	57	.42	3.4
7178-T6	.090	SA	M576	A	59	52	1.0	62	.38	3.5
7178-T6	.090	SA	M576	B	60	59	1.0	63	.40	--
7178-T6	.090	SA	M576	C	64	60	1.0	57	.39	4.2
7178-T6	.090	SA	M576	D	62	60	1.0	51	.38	--
7178-T6	.090	SA	5154	B	58	52	1.4	59	.42	--
7178-T6	.090	SA	5154	E	58	49	1.5	58	.42	--
7178-T6	.090	SA	5554	B	58	53	1.5	54	.41	--
7178-T6	.090	SA	5554	E	57	47	2.0	60	.42	--
7178-T6	.090	SA	5652	B	55	50	2.0	60	.42	--
7178-T6	.090	SA	5652	E	54	46	1.5	57	.42	--

TABLE IV (Continued)

Alloy and Temper	Thickness Inches	Weld Method	Filler Alloy	Post-Weld Treatment	Tensile Tests TS KSI	Tensile Tests YS KSI	Tensile Tests % El (2")	Bulge Tests TS KSI	Bulge Tests Height Inches	Bulge Tests S KSI
7075-T6	.125	DCSP	M576	None	50	48	1.0	43	.41	--
7075-T6	.125	DCSP	5556	None	50	45	1.0	52	.45	--
7075-T6	.125	MIG	5556	None	46	--	1.2	45	.41	--
7075-T6	.125	SA	5554	None	58	52	1.3	54	.40	--
7075-T6	.125	DCSP	5052	A	54	45	1.0	56	.46	--
7075-T6	.125	DCSP	5052	B	63	57	2.5	54	.43	--
7075-T6	.125	DCSP	5052	C	60	54	1.0	50	.41	--
7075-T6	.125	DCSP	5052	D	55	50	1.0	40	.34	--
7075-T6	.125	DCSP	5554	A	56	47	1.0	52	.42	--
7075-T6	.125	DCSP	5554	B	61	55	1.0	45	.36	--
7075-T6	.125	DCSP	5554	C	61	54	1.0	48	.40	--
7075-T6	.125	DCSP	5554	D	62	55	1.0	40	.31	3.2
7075-T6	.125	DCSP	5556	A	57	49	0.5	60	.50	5.1
7075-T6	.125	DCSP	5556	B	63	57	1.0	48	.41	--
7075-T6	.125	DCSP	5556	C	64	58	1.0	53	.42	--
7075-T6	.125	DCSP	5556	D	64	58	1.0	52	.42	4.3
7075-T6	.125	DCSP	M576	B	63	60	1.2	47	.38	--
7075-T6	.125	DCSP	M595	B	64	57	1.2	55	.43	--
7075-T6	.125	DCSP	M594	B	64	58	1.0	55	.43	--
7075-T6	.125	DCSP	M577	B	65	61	1.0	60	.50	3.5
7178-T6	.125	DCSP	M576	None	57	53	1.0	46	.42	--
7178-T6	.125	DCSP	5556	None	56	52	1.0	51	.40	5.5
7178-T6	.125	SA	5554	None	60	58	1.2	62	.43	1.4
7178-T6	.125	DCSP	M576	A	64	61	1.0	52	.37	--
7178-T6	.125	DCSP	M576	B	69	65	1.0	47	.38	--
7178-T6	.125	DCSP	M576	C	69	68	0.5	52	.40	--
7178-T6	.125	DCSP	M576	D	70	68	1.0	58.	.42	4.2

TABLE IV (Continued)

Alloy and Temper	Thickness Inches	Weld Method	Filler Alloy	Post-Weld Treatment	Tensile Tests TS KSI	Tensile Tests YS KSI ✡	Tensile Tests % El (2")	Bulge Tests TS KSI	Bulge Tests Height Inches
7178-T6	.125	DCSP	5556	B	68	65	1.0	41	.28
7178-T6	.125	DCSP	5052	B	68	62	1.0	30	.30
7178-T6	.125	DCSP	M595	B	71	66	0.7	46	.33
7178-T6	.125	DCSP	M594	B	71	67	1.0	43	.34
7178-T6	.125	DCSP	M577	B	73	68	1.0	48	.36

REFERENCES

※ Bulge strengths shown are either "bead on" or "bead off", whichever was highest.

✡ Yield strengths shown are based on 1-2 specimens. Many samples failed prior to 0.2% offset, or were not measured because of possible damage to extensometers.

A - Age 24 hrs at 212°F

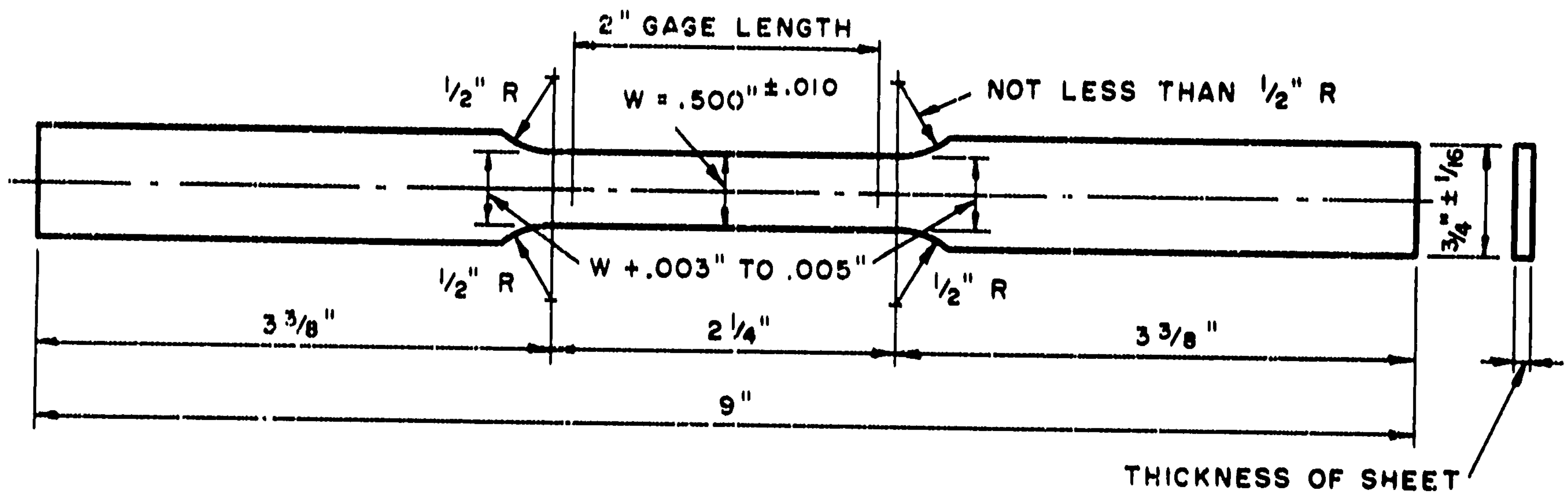
B - Age 168 hrs at 212°F

C - Age 4 hrs at 212°F, cool, Age 8 hrs at 315°F

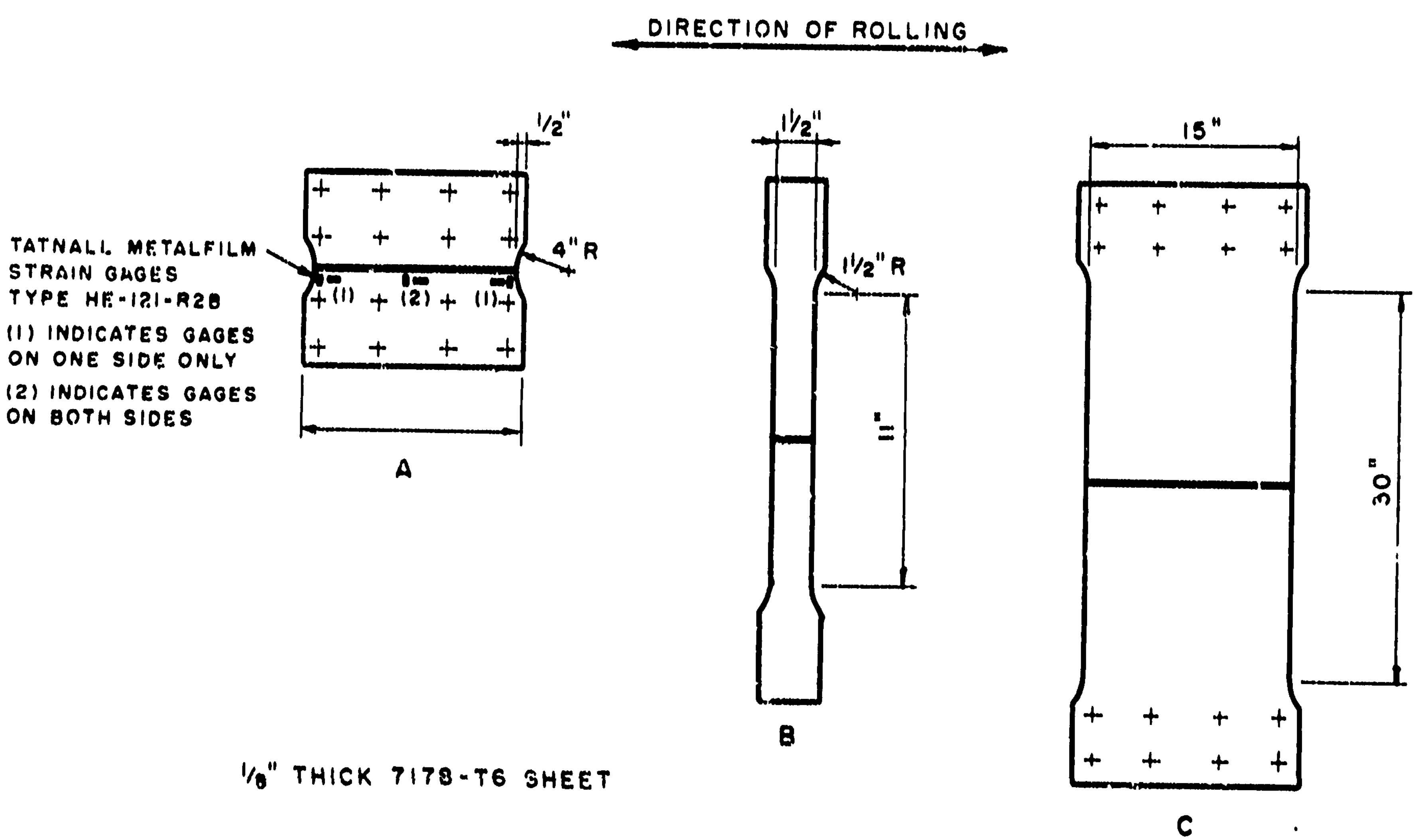
D - Age 8 hrs at 212°F, cool, Age 3 hrs at 325°F

E - Age 4 hrs at 212°F, cool, Age 8 hrs at 250°F

S - Standard deviation



SHEET TENSILE TEST SPECIMEN
FIGURE 1



TEST SPECIMENS
FIGURE 2

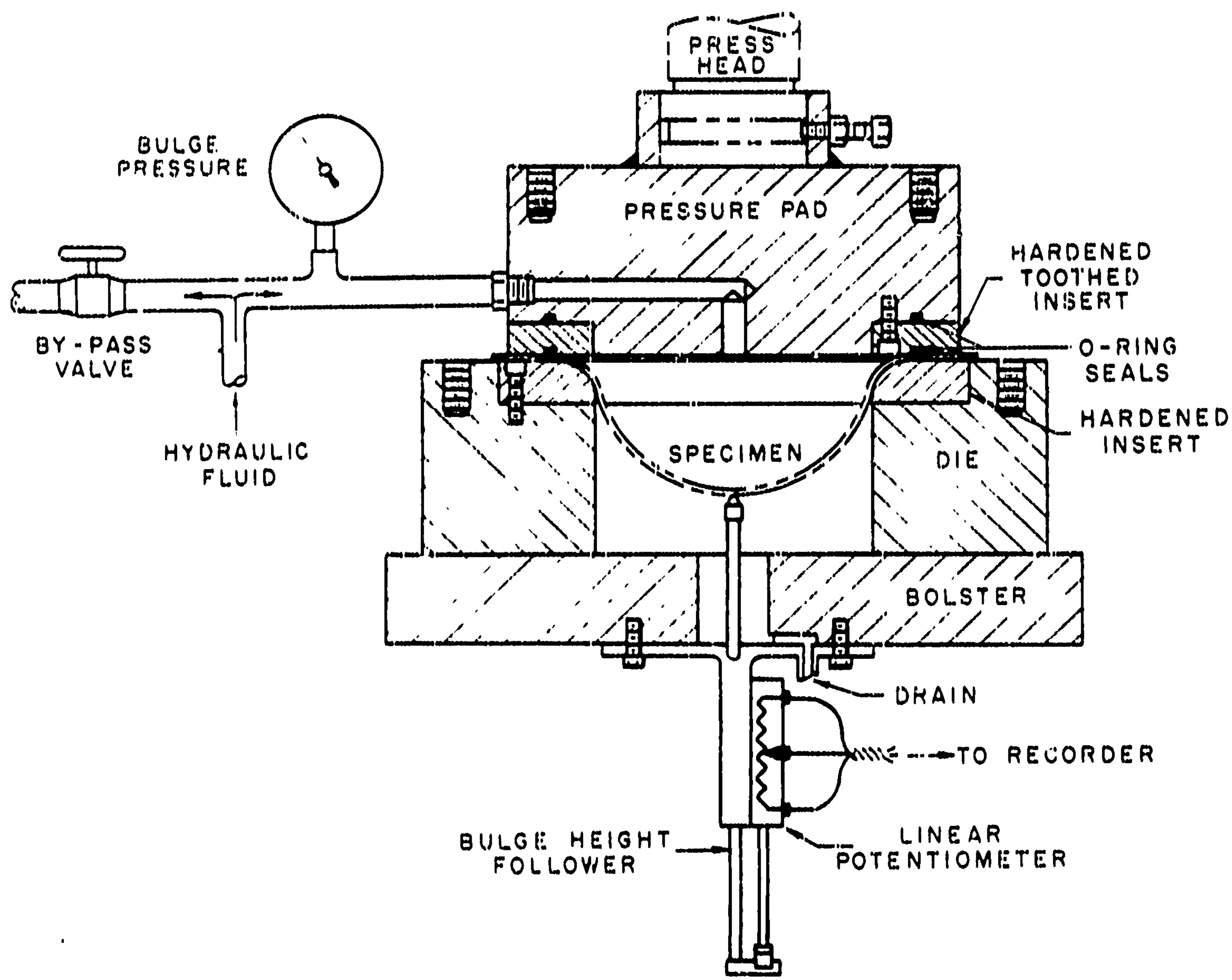


Figure 3

Schematic Drawing of Bulge Tester

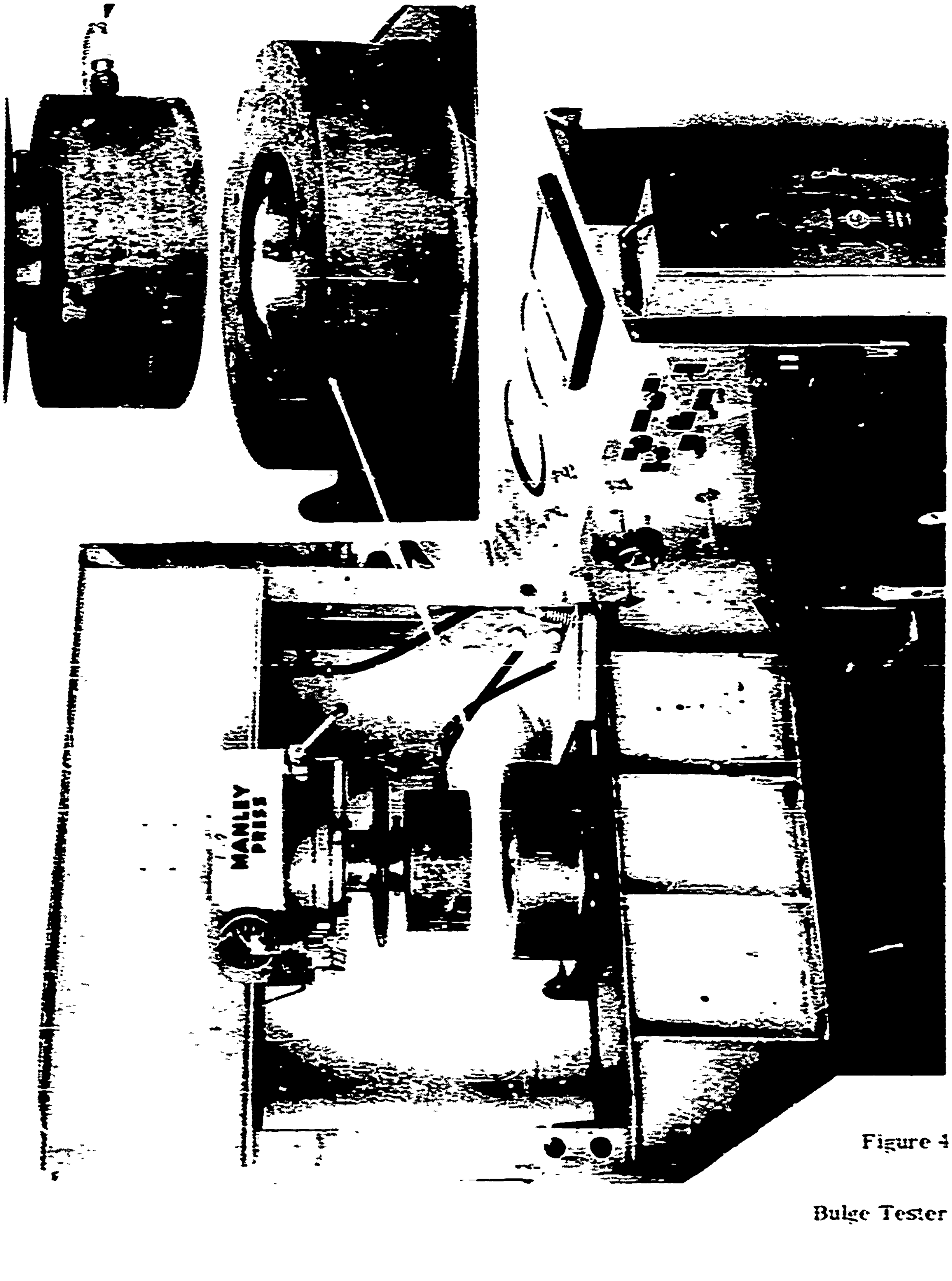
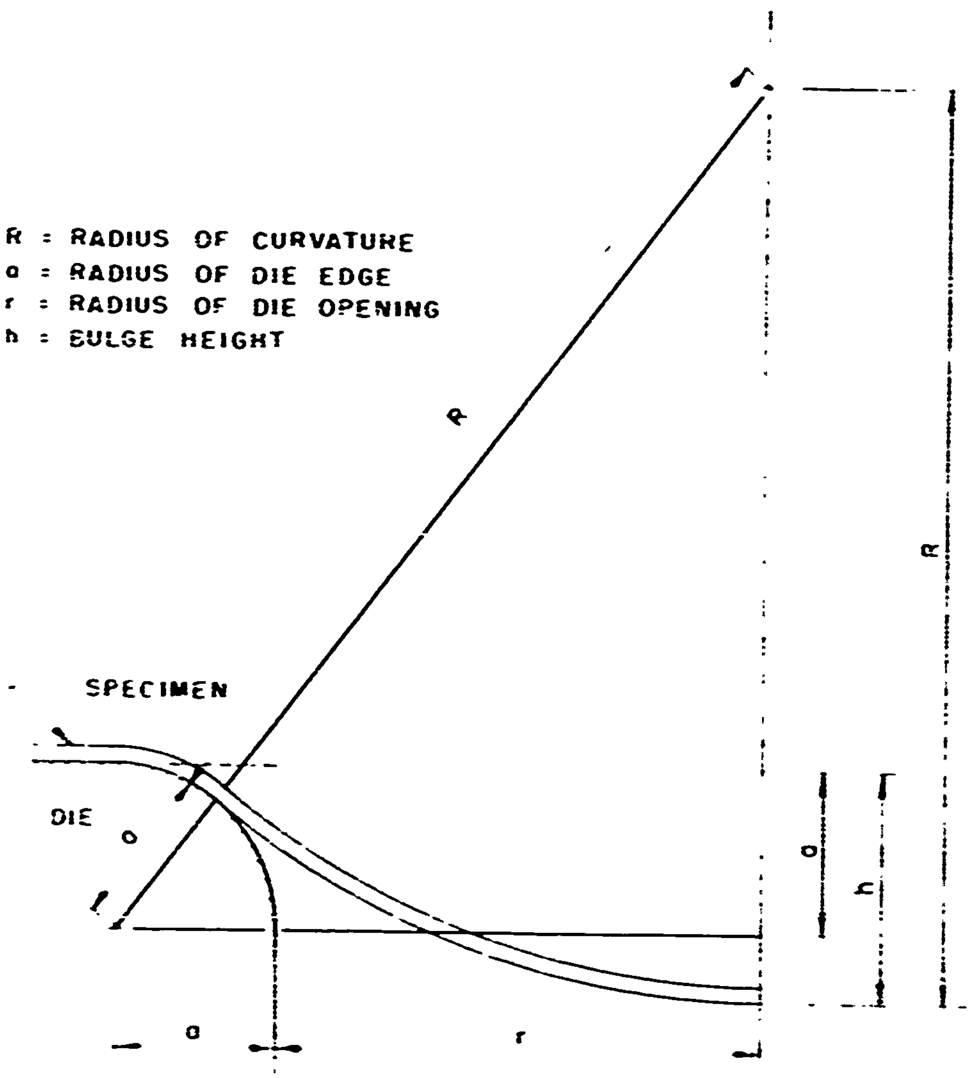


Figure 4

Bulge Tester



(1) BASIC RELATIONSHIP $(R+a)^2 = (r+a)^2 + (R-h+a)^2$

(2) SOLVE FOR R $R = \dfrac{r^2 + h^2 + a^2 + 2ar - 2ah}{2h}$

(3) SUBSTITUTE DIE DIMENSIONS $R = \dfrac{h^2 - 2h + 25}{2h}$

a = 1"

r = 4"

Figure 5

Radius of Curvature Calculation

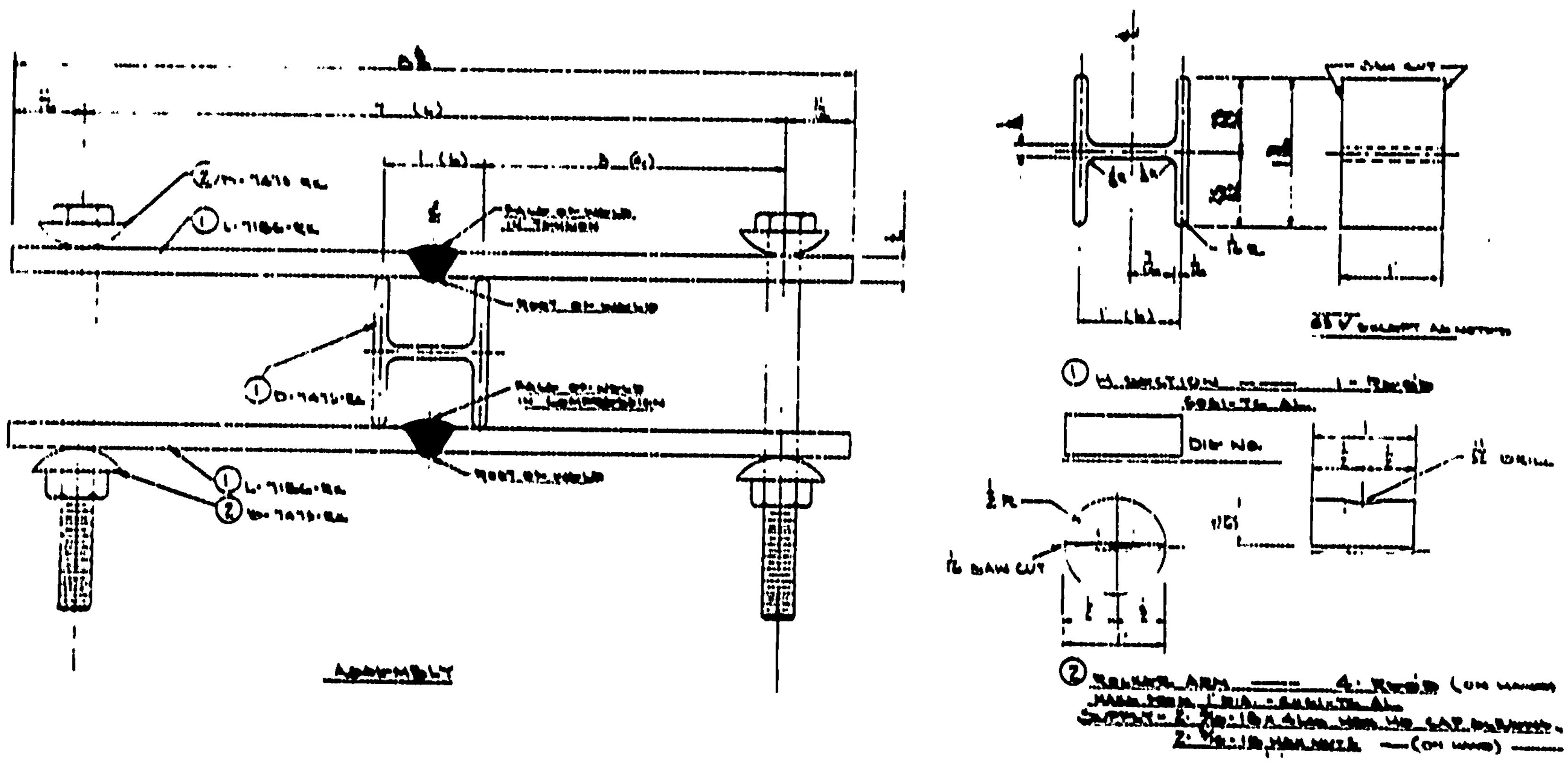


Figure 6

Stress Corrosion Specimen

Fig. 7

Typical DCSP-TIG Weld, Copper Backup

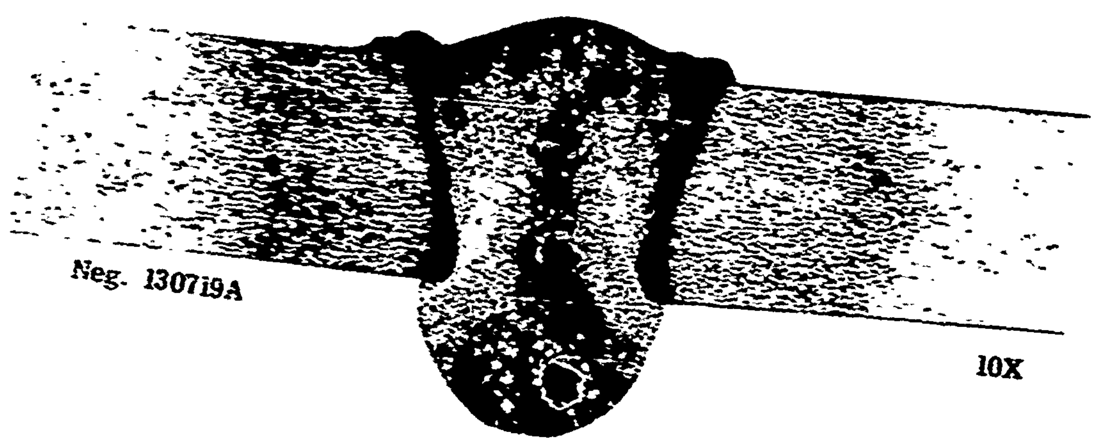
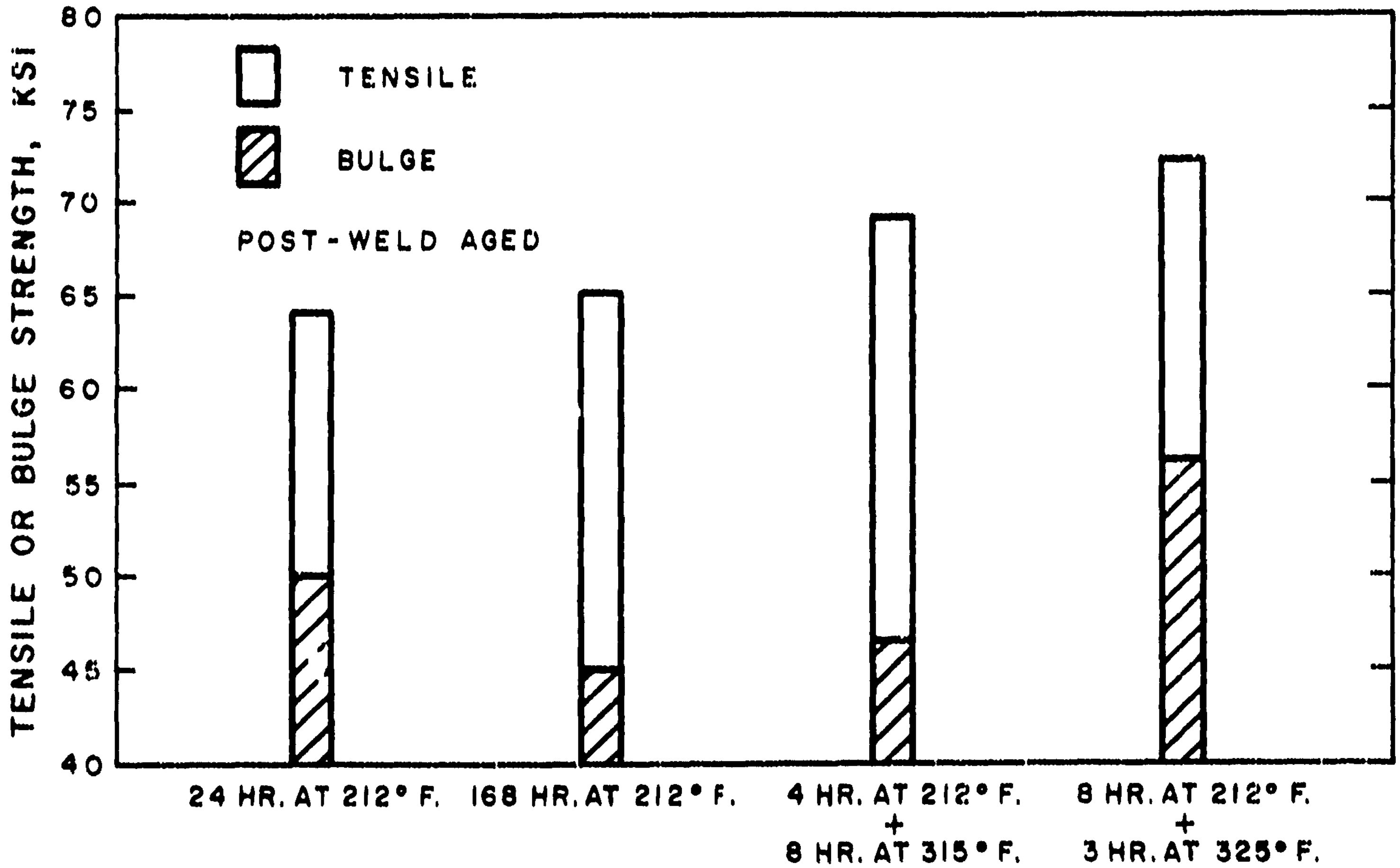


Fig. 8

Typical MIG - Short Arc Weld, Free Drop Through



1/8 INCH 7178-T6 WELDED WITH M576

FIGURE 9

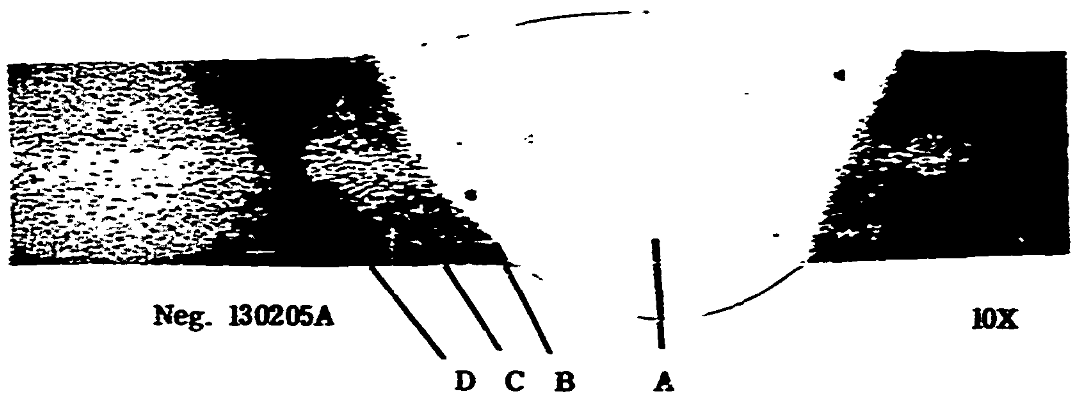


Fig. 10

1/8 inch 7178-T6 DCSP Welded With M576
Shows Areas Examined at Higher Magnification

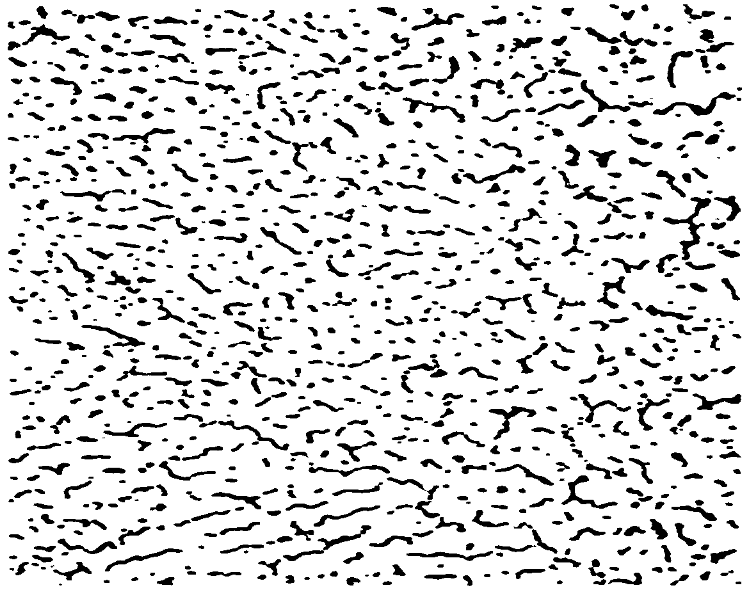


Figure 11

Neg -131205 500X

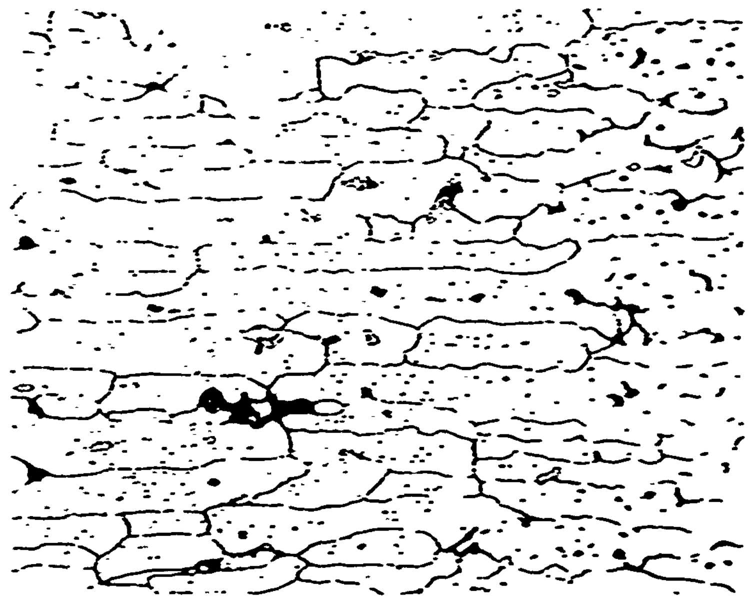
Weld Bead (Area A) 7178-T6, M576 Filler
As-Welded

Figure 12

Neg 131204 500X

Weld Bead (Area A) 7178-T6, M576 Filler Post-
Weld Aged 168 hrs at 212. F

Base Metal

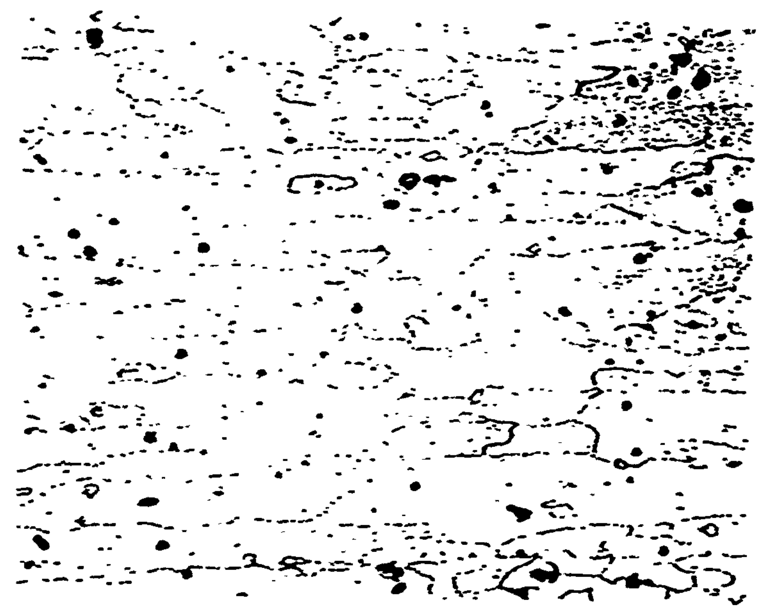


Weld Bead

Figure 13

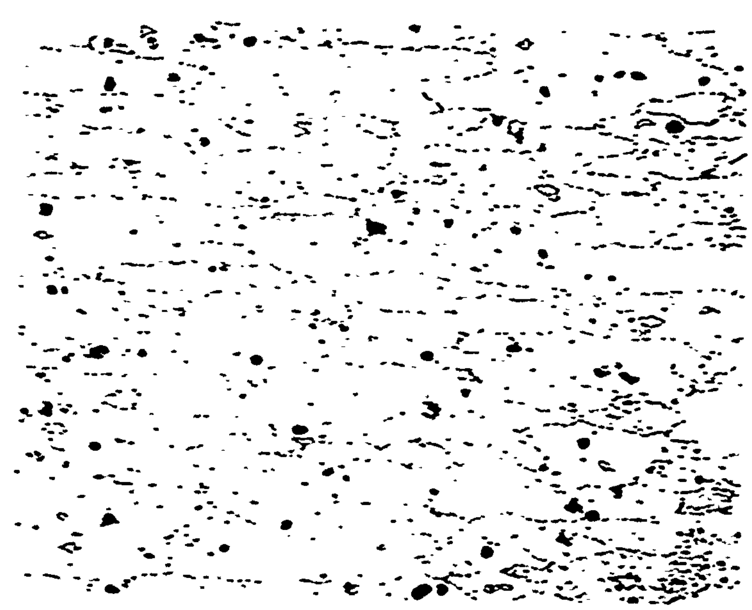
Neg. 130209 500X

Area B, Transition Zone, 7178-T6 Base Metal M576 Filler, Aged 168 hrs at 212° F.



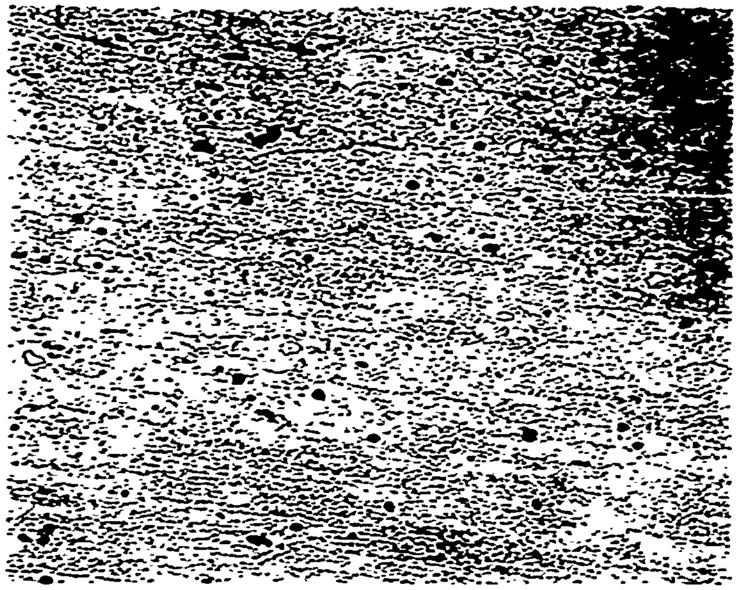
Neg. 130133 Fig. 14 500X

Area C, Heat Treated Zone, 7178-T6, As-Welded



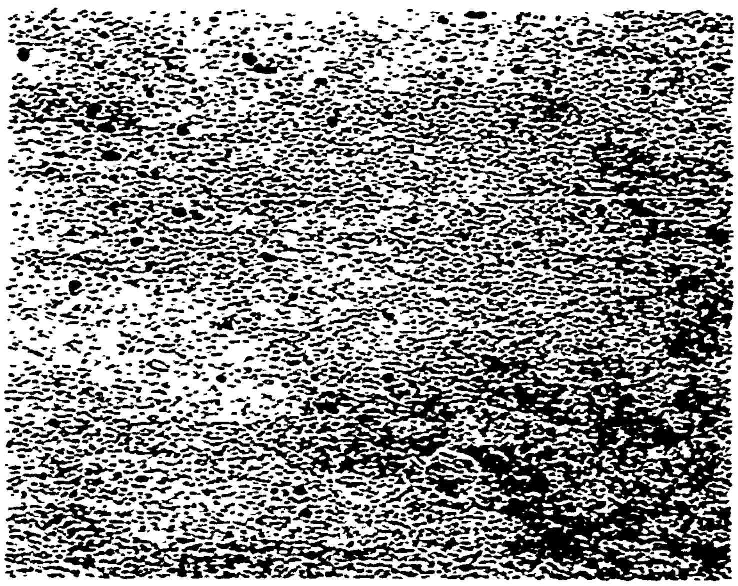
Neg. 130181 Fig. 15 500X

Area C. Heat Treated Zone. 7178-T6, Post Weld Aged 168 hrs. at 212°F



Neg. 130194 Fig. 16 500X

Area D, Overaged Zone, 7187-T6, As-Welded



Neg. 130182 Fig. 17 500X

Area D, Overaged Zone, 7178-T6, Post-Weld Aged 168 hrs. at 212°F

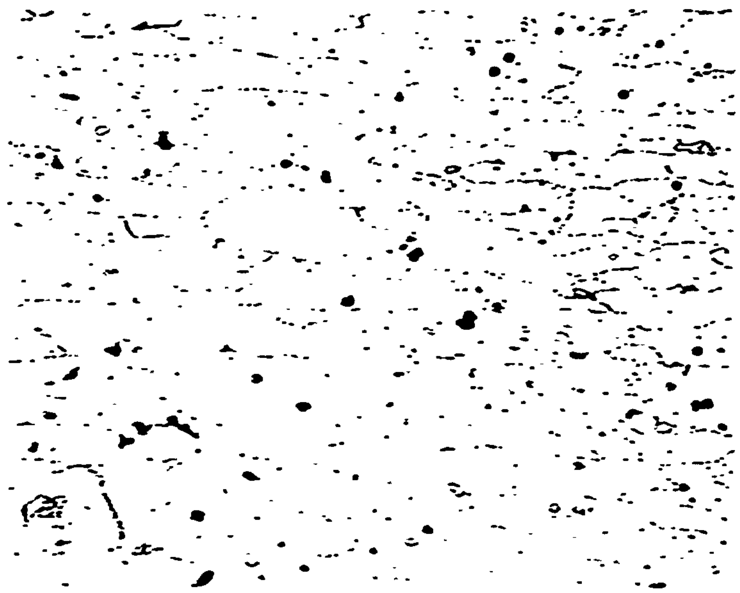


Figure 18

Neg 130195 500X

Area C, Heat Treated Zone, 7075-T6, As-Welded

Figure 19

Neg 130183 500X

Area C, Heat Treated Zone, 7075-T6, Post Weld Aged 168 hrs at 212°F.

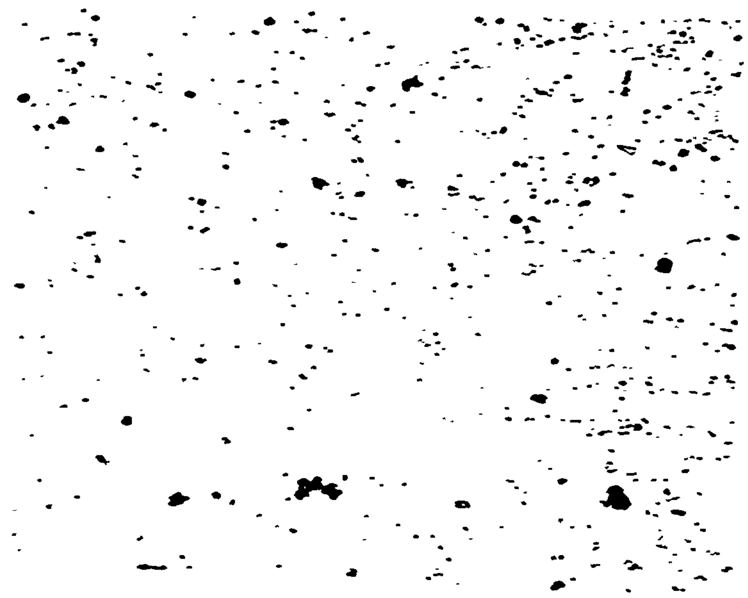


Figure 20

Neg 130196 500X

Area D, Overaged Zone, 7075-T6, As-Welded

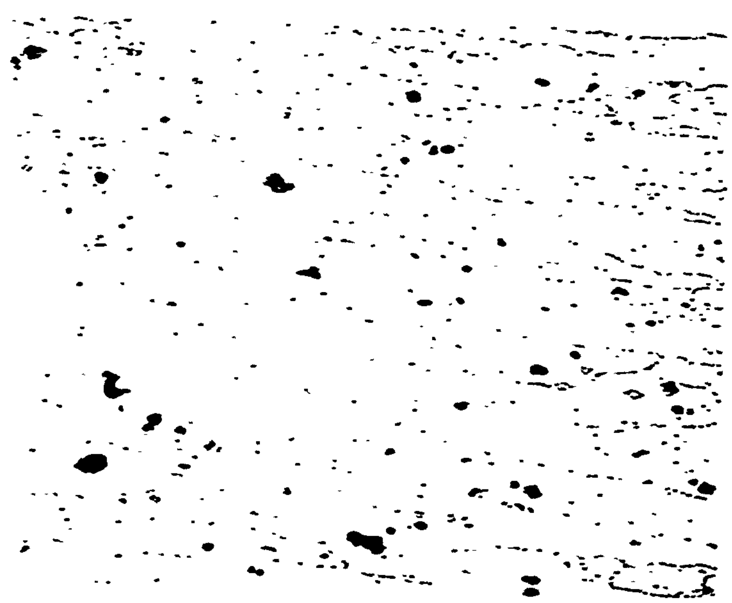
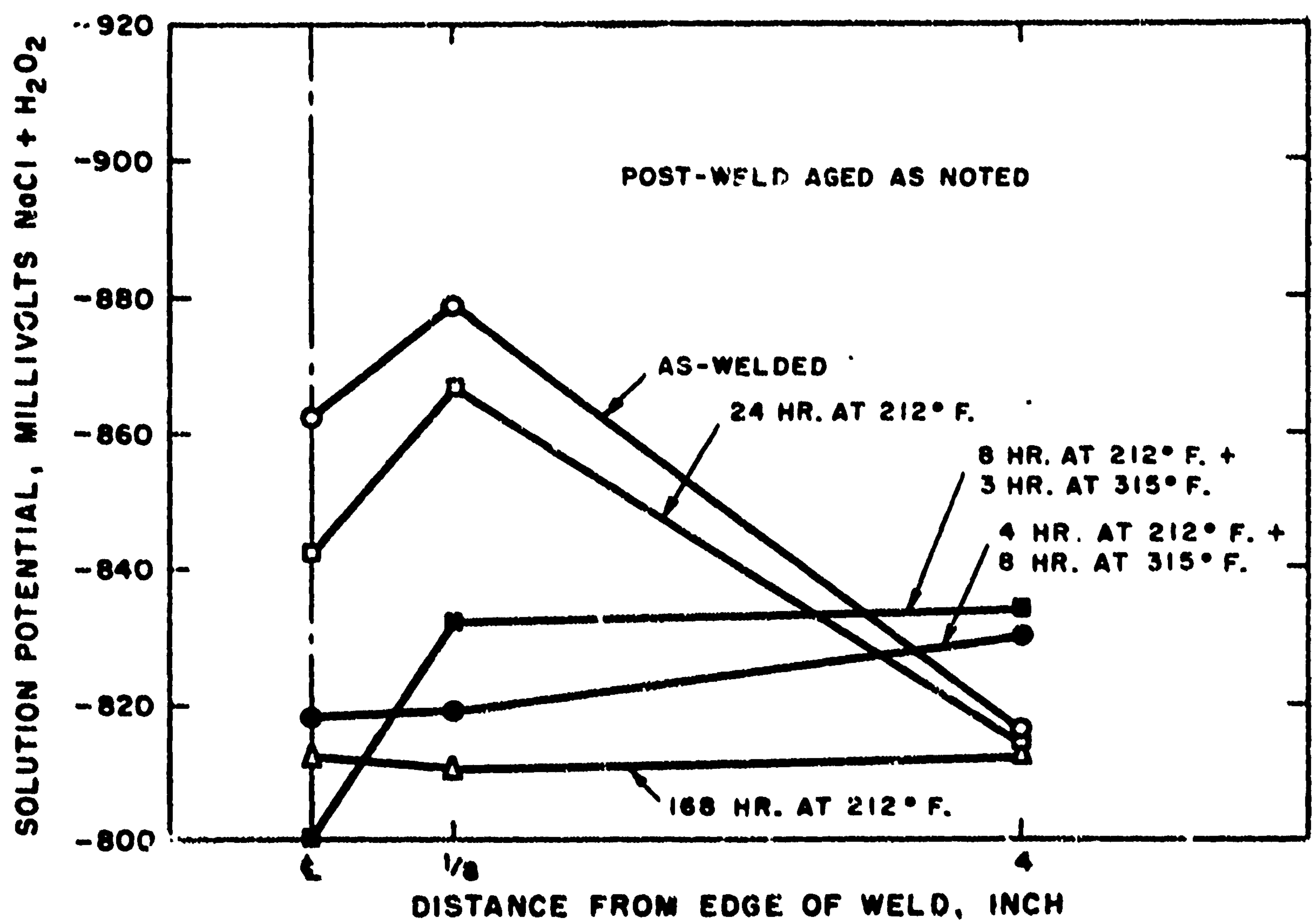


Figure 21

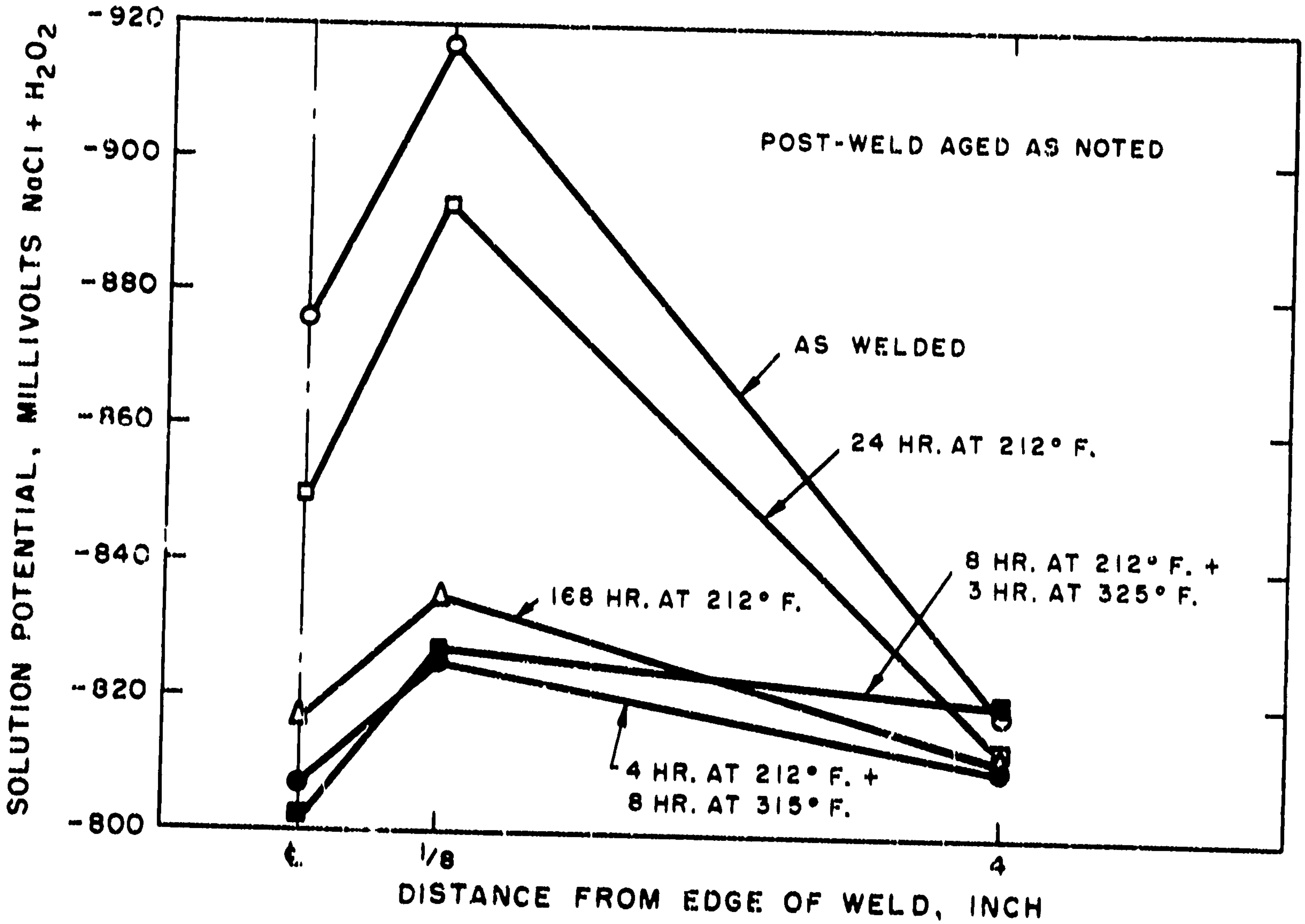
Neg 130184 500X

Area D. Overaged Zone, 7075-T6. Post-Weld Aged 168 hrs at 212 °F.



7075-T6 DCSP-TIG WELDED WITH M576

FIGURE 22



7178-T6 DCSP-TIG WELDED WITH M576

FIGURE 23